AMSD Figure Certification Plan:

System Approach and Error Analysis

Patrick J. Reardon

Brian Robinson

James Hadaway

UAH

Phil Stahl

MSFC

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Outline

- **System Approach (the components and their layout)**
    - Figure measurement instrumentation
    - ROC measurement instrumentation

- **Coordinates and Assumptions**

- **Measurement Procedure**

- **Error Analysis**

- **Further Efforts**

- **Additional Tasks**

- **Conclusions**

System Approach

Figure measurement instrumentation

    IPI

        Instantaneous Phase-shifting Interferometer

        Surface accuracy <3 nm rms (w/ ref sub)

        Phase shifting using spatial carrier method

    Diverger on IPI is f/5

Figure measurement instrumentation

Diffractive Null

Vendor: Diffraction International

Fiducial Structures Encoded in Null

for alignment of:

- **Null to Interferometer**
- **Null/Interferometer to Window**
- **Null/Interferometer to Mirror**
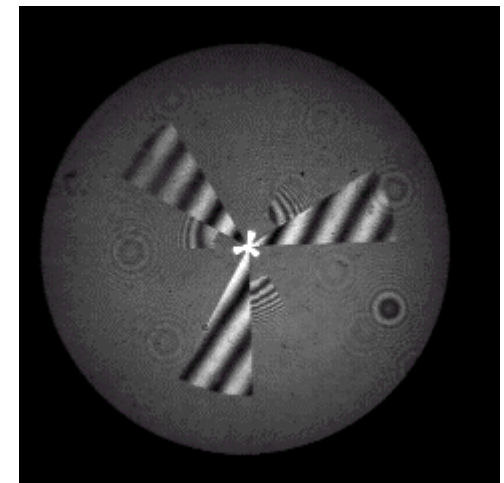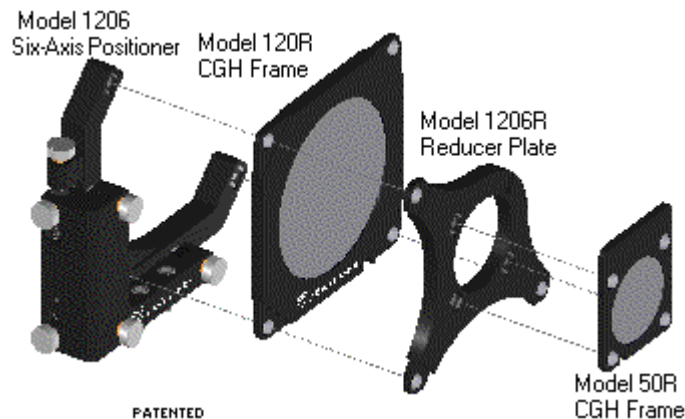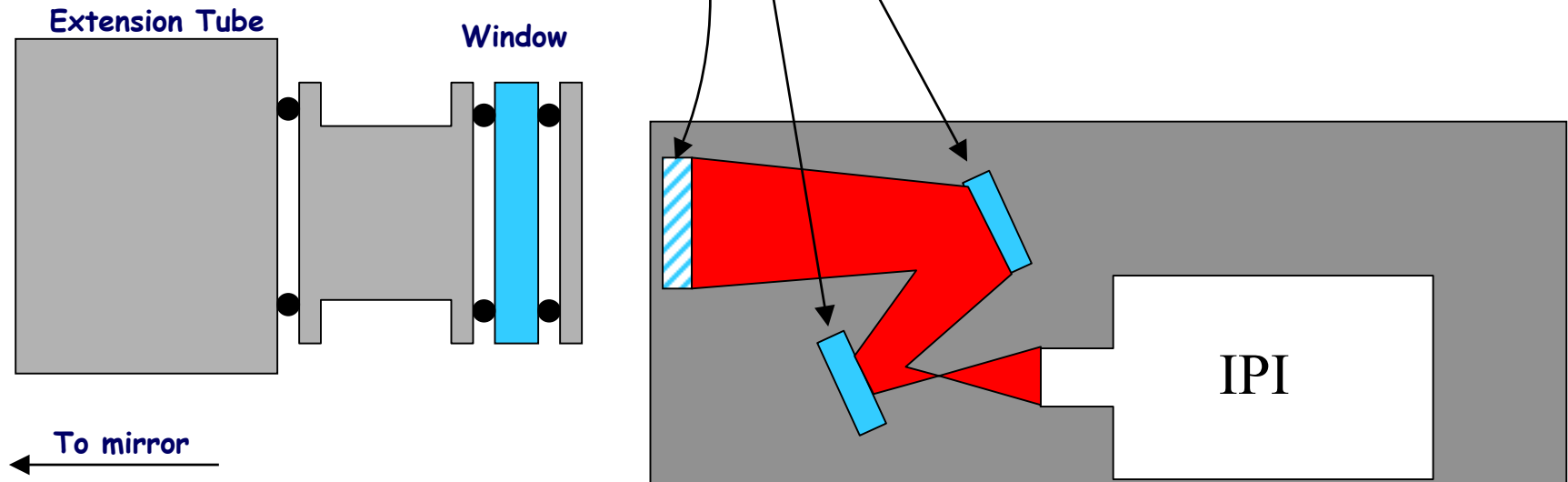
System Approach

Figure measurement instrumentation

Pallet Layout

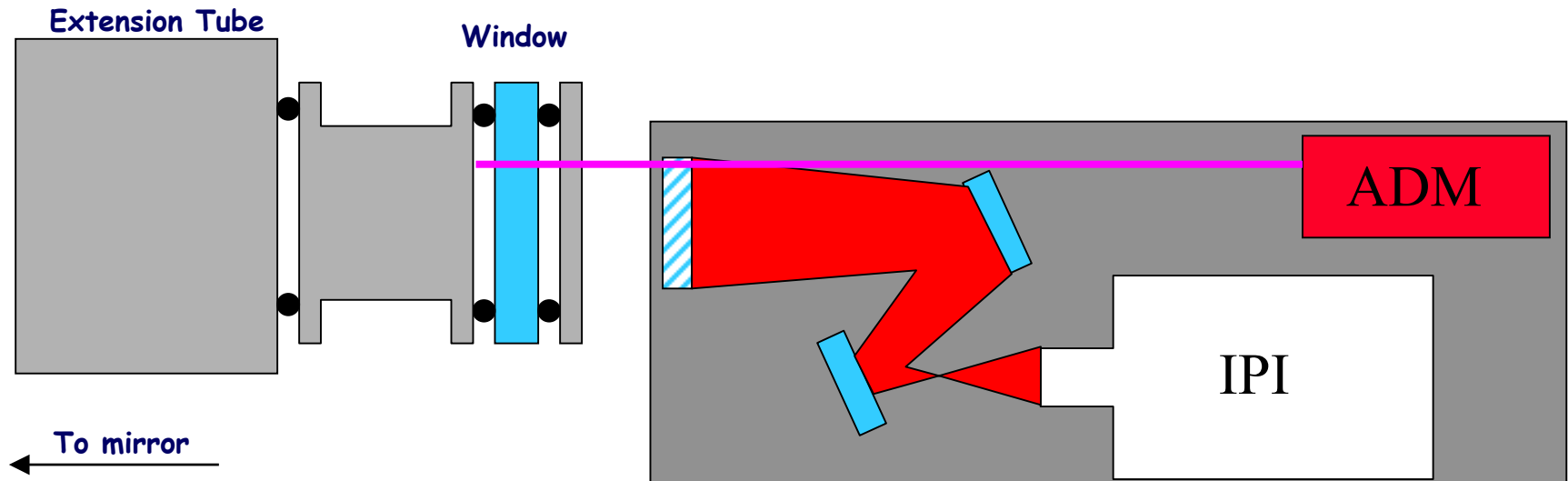**Contains null, 2 fold mirrors, and IPI.**

Extension Tube

Window

To mirror

IPI

ROC measurement instrumentation

ADM from Leica

~0.020mm accuracy

- **Measure distance to null**
- **Measure distance to mirror**

Extension Tube

Window

To mirror

ADM

IPI

System Approach

Motion control of sensor pallet

Require precise and repeatable motion

- **Hexapod from Physik Instrumente**
    - *6-DOF*
    - *200kg load capacity*
    - *±0.002mm repeatability*
    - *True path control*
    - *Definable pivot point*

IPI

Coordinates (side view)

+Y(up, in mm)

θy (LH in degrees)   θz (RH in degrees)

-Z(in mm)

θx (LH in degrees)

+X(in mm)

Mirror

Window

DOE

Interferometer

5-Dof Stage

6-Dof Stage

6mm

15.9mm

660mm   100mm   9300mm

Coordinates and Assumptions

Coordinates (top view)

Interferometer

DOE

Window

COC

Mirror

-X

-Z

1400mm

7.9 deg.

Vertex
of Parent
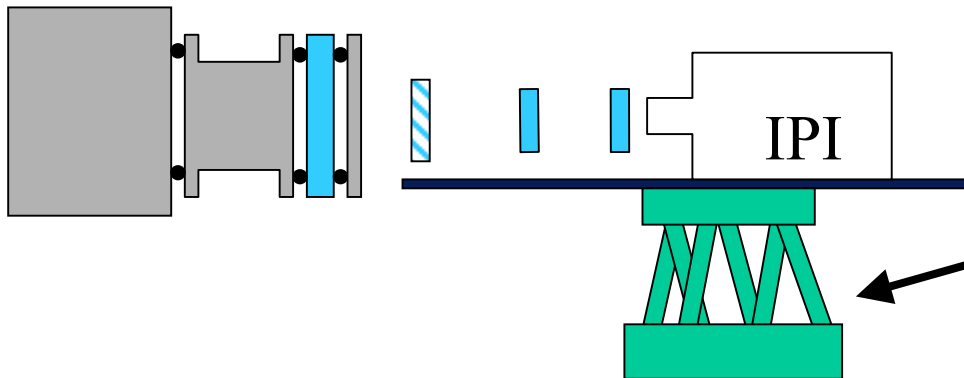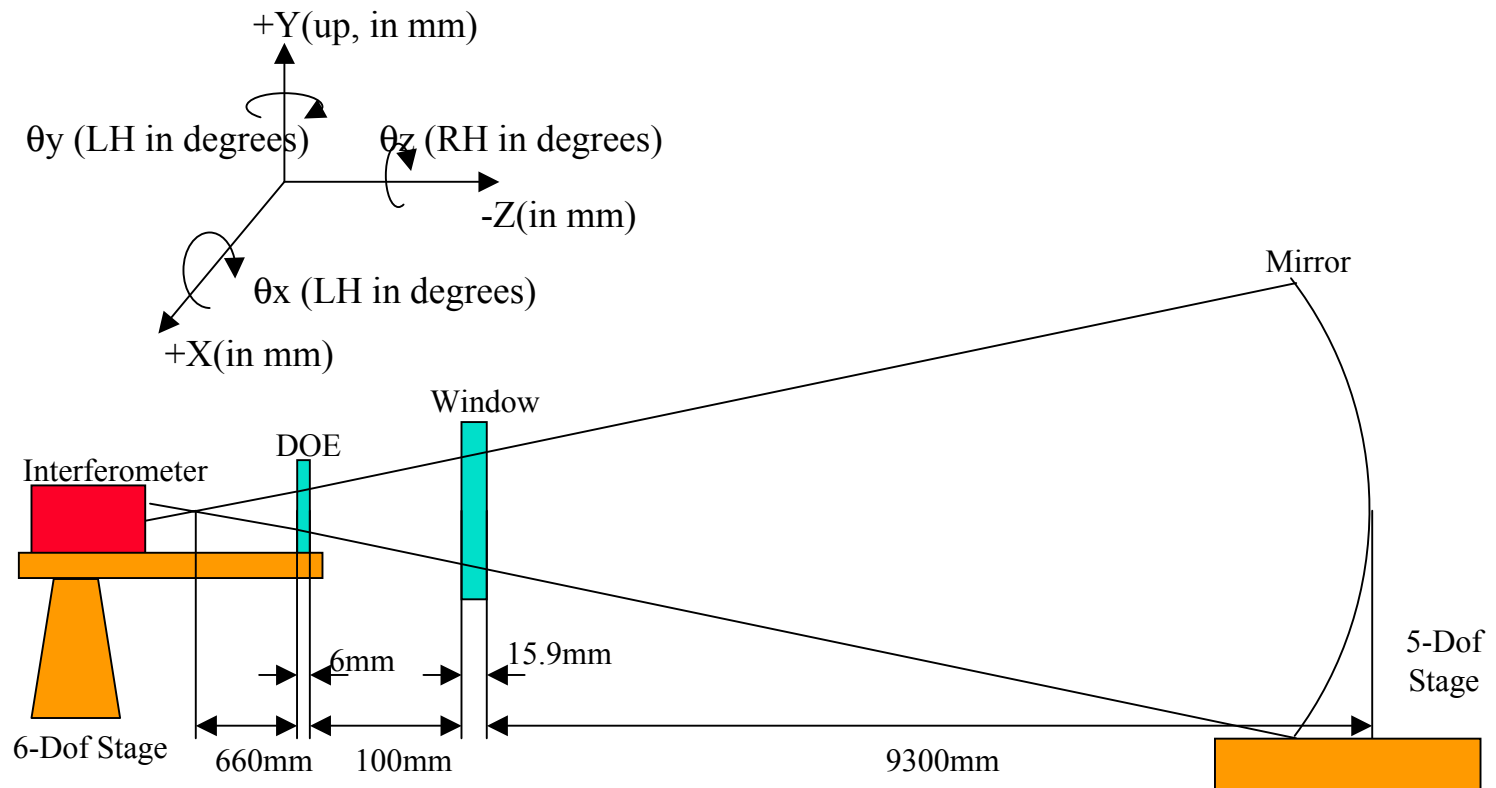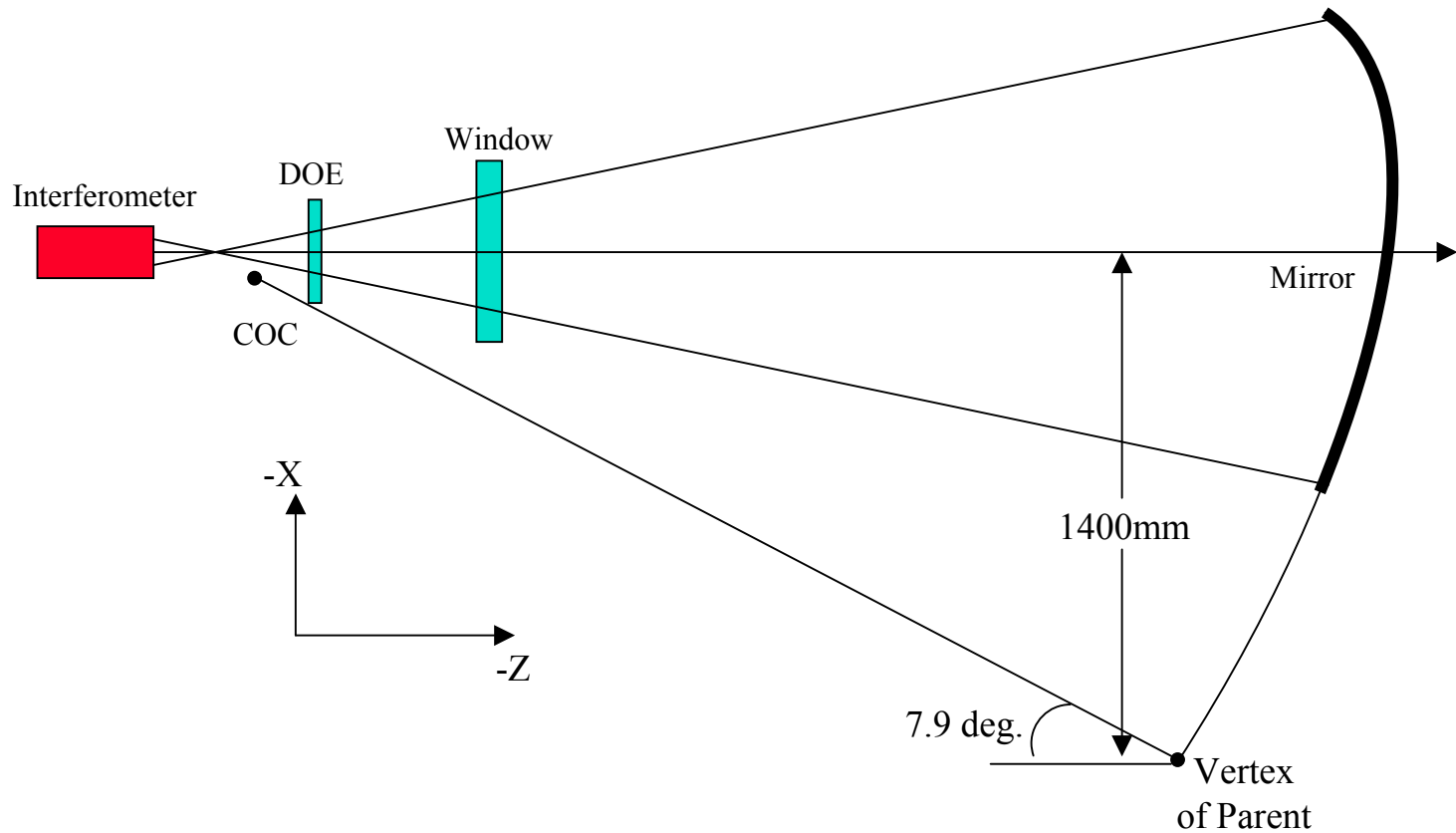
Fiducial Coordinates

Looking towards mirror surface

D=4m

(-1393,0)

(0,0)
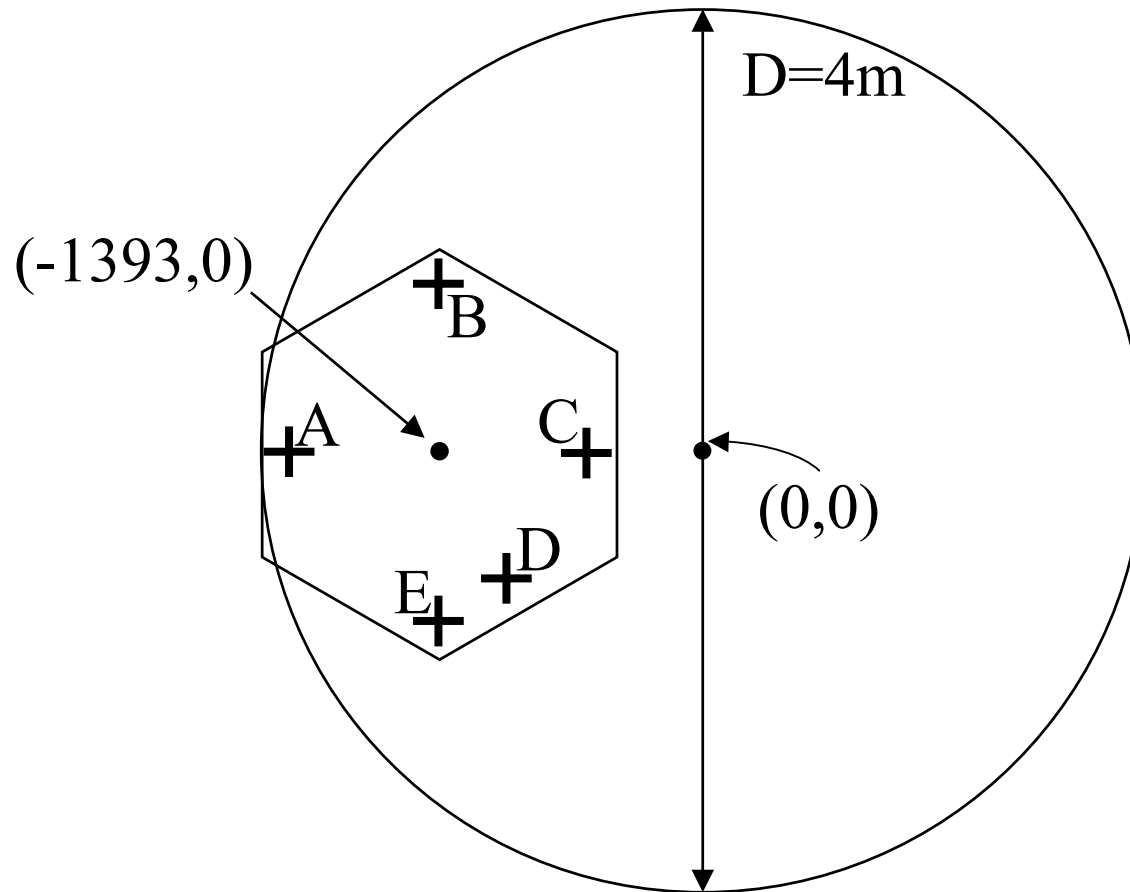
A = (-1900,0)
B = (-1393,550)
C = (-886,0)
D = (-1155,-412)
E = (-1393,-550)

Measurement Procedure

ALIGNMENT PHASE(1)

1.) Align null to interferometer

  Use alignment CGH & CGH adjustments.

  Translate CGH stage predetermined amount (to account for difference in thickness between alignment & null CGH substrates).

  Remove alignment CGH and insert null CGH.

2.) Verify alignment of interferometer to window

  Use diffractive zone on null CGH.

  Designed for normal incidence.

  Tolerance ±0.1 degrees.

This sets up the sensor pallet to produce the desired paraboloidal wavefront at the predetermined position.

ALIGNMENT PHASE(2)

3.) Align mirror to pallet by viewing fiducials

>   Should achieve better than ±0.2mm lateral alignment

4.) Set spacing of pallet and mirror using ADM to insure mirror segment is where perfect paraboloid should be.

5.) Repeat 3 & 4 if necessary.

This insures that the wavefront incident on the mirror segment has a 10m RoC paraboloidal shape. If perfectly aligned, interferogram would only show difference between the perfect paraboloidal wavefront and the mirror surface.

Measurement Procedure

ALIGNMENT PHASE(3) & DATA ACQUISITION

6.)   Acquire a data set at position (x0, y0, z0)

   Multiple frames, averaging

7.)   Decenter pallet 1mm in x-direction, then tilt mirror to direct return spot back onto point source (minimize tilt resulting from decenter)

   Position (x0+1, y0, z0)

   This can be achieved with the hexapod alone.

8.)   Acquire a data set

9.)   Move to (x0, y0+1, z0), again minimizing tilt, and acquire data.

10.) Move to (x0, y0, z0+1), again maintaining minimum tilt, and acquire data.

ALIGNMENT PHASE(3) & DATA ACQUISITION

11.) Each data set is then processed in the manner to be described and yields an (x,y,z) vector giving the misalignment in each direction. The vectors from the four preceding measurements are averaged.

12.) The pallet is then moved according to the final averaged (x,y,z) vector and the 5th & final data set is acquired. This location should correctly align the mirror segment to the paraboloidal wavefront.

Final data yields interferogram of surface deformations.

(An alternative method would be to analytically determine the surface deformations using only the results of the first four measurements.)

Measurement Procedure

The testing procedure is based on seminal works by

- *M. Rimmer, "Analysis of Perturbed Lens Systems," Applied Optics, 9, 533-537 (1970).*

- *G.C. Dente, "Separating Misalignment from Misfigure in Interferograms of Off-Axis Aspheres," SPIE 429, 187-193 (1983).*

- *E.W. Young and G.C. Dente, "The Effects of Rigid Body Motion in Interferometric Tests of Large-Aperture, Off-Axis, Aspheric Optics," SPIE 540, 59-68 (1985).*

- *H.P. Stahl, "Testing Aspheric Components," Course Notes Published by Stahl Optical Systems, Inc., (1999).*

Separation of misfigure from misalignment is the primary difficulty in the metrology of aspheres.

We have determined that using an analytical/numerical approach, along with the available instrumentation, to align & measure an AMSD segment will readily meet the AMSD testing requirements.

Explanation:(1)

Premise: Every vendor will provide a mirror that is a perfect 10m RoC paraboloid ..… that has some deformations.

$$S(x,y) = P(R=10m,x,y) + D(x,y)$$

Unfortunately, misalignments of a perfect paraboloid yield aberrations which could be misinterpreted as deformations.

Therefore, misalignment-induced errors must either be eliminated prior to the measurement (perfect alignment) or subtracted from the data after the measurement.

Explanation:(2)

Misaligning a perfect paraboloid segment in x, (εx), while minimizing tilt with rotations of the segment about its center, yields functions linear in x for several Zernike terms.

Misaligning a perfect paraboloid segment in y, (εy), and z, (εz) also yields functions linear in y and z for several Zernike terms.

- *a# = acquired Zernike value from test*

–Power	$a4 = \varepsilon x \cdot mx4 + \varepsilon z \cdot mz4$
–0° Astigmatism	$a5 = \varepsilon x \cdot mx5 + \varepsilon z \cdot mz5$
–45° Astigmatism	$a6 = \varepsilon y \cdot my6$
–0° Coma	$a7 = \varepsilon x \cdot mx7 + \varepsilon z \cdot mz7$
–90° Coma	$a8 = \varepsilon y \cdot my8$

Measurement Procedure

Explanation:(3)

Misaligning a deformed paraboloid segment in x, y, or z yields functions linear in εx, εy, & εz for same Zernike terms and with <u>same linear dependence</u>. The only difference is a bias term containing the magnitude of the deformations, d#.

An extensive CodeV analysis confirmed that the alignment-induced aberrations of identically misaligned perfect and misfigured paraboloids are essentially identical.

–Power	$a4 = \varepsilon x \cdot mx4 + \varepsilon z \cdot mz4 + d4$
–0° Astigmatism	$a5 = \varepsilon x \cdot mx5 + \varepsilon z \cdot mz5 + d5$
–45° Astigmatism	$a6 = \varepsilon y \cdot my6 + d6$
–0° Coma	$a7 = \varepsilon x \cdot mx7 + \varepsilon z \cdot mz7 + d7$
–90° Coma	$a8 = \varepsilon y \cdot my8 + d8$

Explanation:(4)
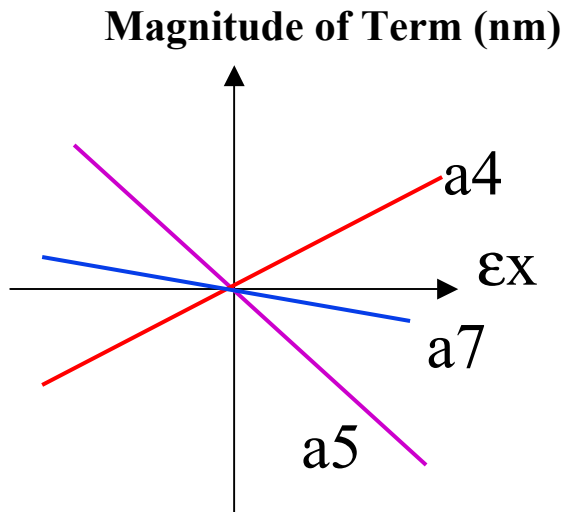
Perfect Paraboloidal Segment
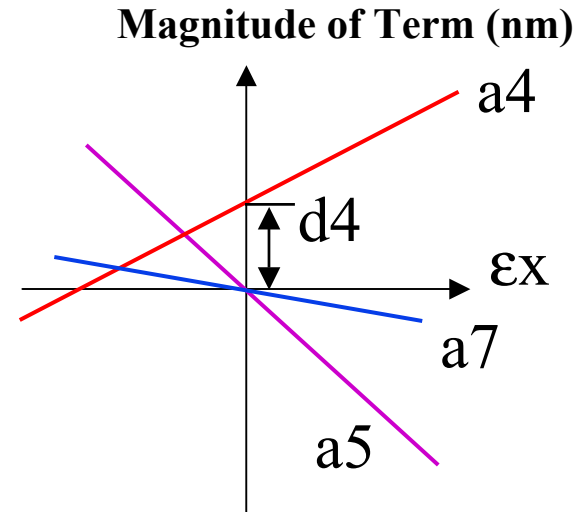
Paraboloidal Segment Deformed by Zernike Power (d4)

Measurement Procedure

Explanation:(5)

If we can determine (εx, εy, εz), we can we can realign to set (εx, εy, εz) = (0,0,0), or we can subtract off the misalignment-induced aberrations after the fact.

To determine values for εx, εy, & εz, the problem is approached as a least squares minimization.

Using the fact that Zernikes are orthonormal, the least squares calculation yields a function which, after a bit of algebraic manipulation, yields functions for the misalignments.

Explanation:(6)

Equations for calculating misalignment of mirror

$$C\varepsilon x = \frac{mx4 \cdot a4 + mx5 \cdot a5 + mx7 \cdot a7}{mx4^2 + mx5^2 + mx7^2}$$

$$C\varepsilon y = \frac{my6 \cdot a6 + my8 \cdot a8}{my6^2 + my8^2}$$

$$C\varepsilon z = \frac{mz4 \cdot a4 + mz5 \cdot a5 + mz7 \cdot a7}{mz4^2 + mz5^2 + mz7^2}$$

Note that the calculated x and z misalignments, Cεx and Cεz, use the same Zernike terms. However, the values for the slopes are quite different.

Explanation:(7)

- **The measurement procedure currently plans on 4 displaced measurements.**

- **Taking data in the nominal x, y, & z directions reduces errors introduced by cross terms.**

- **Provides Consistency Checks:**
  - **All should point to the same location as optimum.**
  - **Results can be used to experimentally evaluate and validate the slope terms.**

Error Analysis

- **The mirror is required to have an RMS surface figure error less than 50nm.**

- **This deformation can take any form, so we uniformly and randomly distribute it among the first 16 low order terms, d1 - d16, yielding σd^2 values for the Zernike terms.**

- **The σ^2 of the calculated misalignments are then determined:**
  - **0.018mm y-alignment uncertainty which corresponds an RMS surface uncertainty of 2.8nm.**
  - **0.064mm x-alignment uncertainty which corresponds to an RMS surface uncertainty of 13nm.**
  - **0.011mm z-alignment uncertainty which corresponds to an RMS surface uncertainty of 9.5nm.**

- **And finally, RSS these three uncertainties to yield a misalignment-induced surface uncertainty of 16.3nm RMS.**

- **Currently working to reduce this uncertainty value with a total measurement uncertainty goal of 10-12 nm RMS.**

Error Analysis Roll-up

The following roll-up is preliminary and not each term will be discussed.
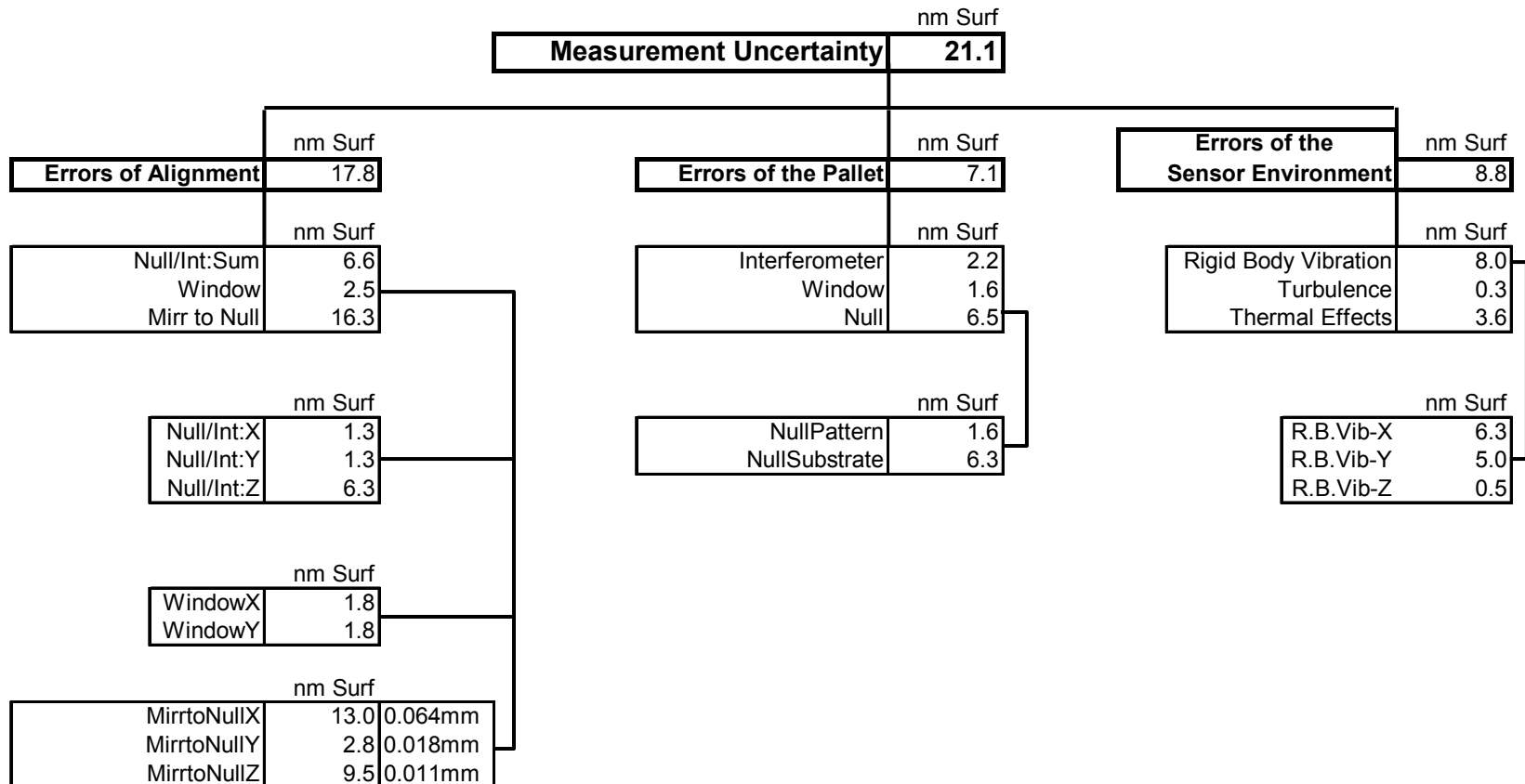
This entire analysis will be completely firmed up and documented by the end of July, 2002.

Numbers are either

- **derived from analytical calculations**
- **measured performance values from devices in-house**
- **values noted in previous experiments at the XRCF**
- **engineering guesses based on combinations of past test experience and AMSD models**

RMS Surface Error   *PRELIMINARY* (goal is total uncertainty of 10-12 nm)

Error Analysis as of 5-20-02

	nm Surf
Measurement Uncertainty	**21.1**

	nm Surf			nm Surf		**Errors of the**	nm Surf
Errors of Alignment	17.8		**Errors of the Pallet**	7.1		**Sensor Environment**	8.8

	nm Surf			nm Surf			nm Surf
Null/Int:Sum	6.6		Interferometer	2.2		Rigid Body Vibration	8.0
Window	2.5		Window	1.6		Turbulence	0.3
Mirr to Null	16.3		Null	6.5		Thermal Effects	3.6

	nm Surf			nm Surf			nm Surf
Null/Int:X	1.3		NullPattern	1.6		R.B.Vib-X	6.3
Null/Int:Y	1.3		NullSubstrate	6.3		R.B.Vib-Y	5.0
Null/Int:Z	6.3					R.B.Vib-Z	0.5

	nm Surf
WindowX	1.8
WindowY	1.8

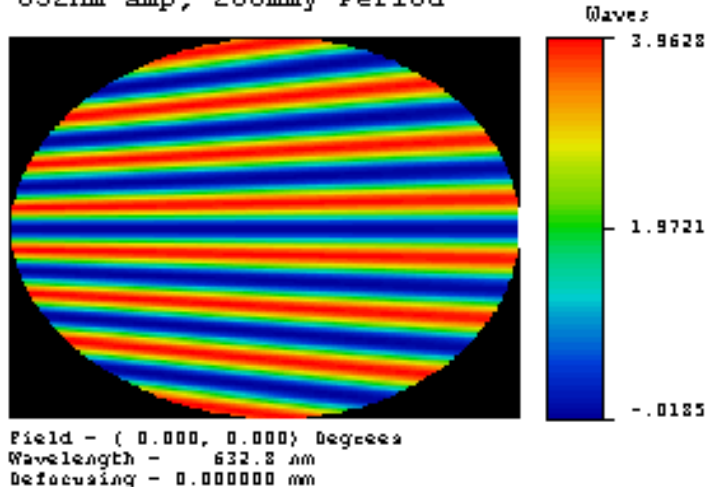|	nm Surf	
MirrtoNullX	13.0	0.064mm
MirrtoNullY	2.8	0.018mm
MirrtoNullZ	9.5	0.011mm

Further Efforts

- **Do simulations, especially using predicted gravity sag from FEA, looking for problematic cases.**

- **Develop algorithms further to reduce uncertainty**
  - **Extend analytical solution into higher order Zernikes.**
  - **Use constraints to bound solution.**
    - *Knowledge of εz (ADM) vs calculated εz*
  - **Look at individual contributions, ratios of terms.**
  - **Optimize number of terms through zero versus minimizing rms.**
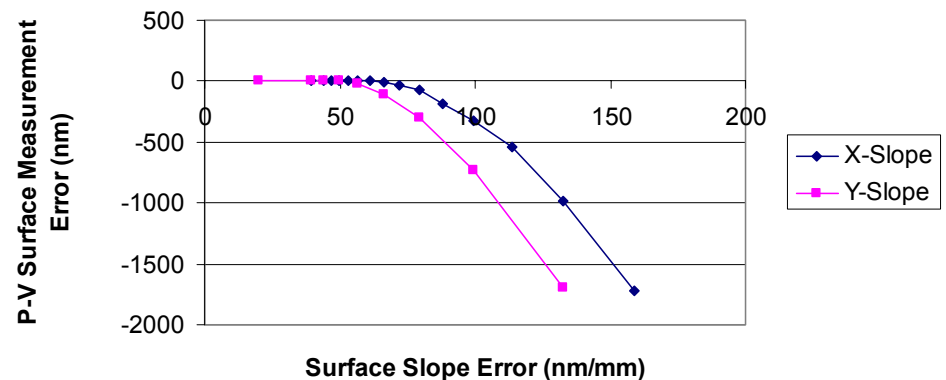
Additional Tasks

- **Pupil distortion**
  - **Plan to work with vendors to satisfy their requirements.**
  - **Also plan to develop independent method.**

- **Retrace Error**
  - **Evaluating retrace error both numerically and analytically.**
  - **Numerical method applies a sinusoidal deformation on mirror surface and evaluates errors as period of modulation increases.**

WAVEFRONT ABERRATION

632nm amp, 200mmy Period

Waves

3.9628

1.9721

-.0185

Field - (0.000, 0.000) Degrees
Wavelength -   632.8 nm
Defocusing - 0.000000 mm

Retrace Error (nm) vs Surface Slope Error (nm/mm)

P-V Surface Measurement Error (nm)

Surface Slope Error (nm/mm)

- X-Slope
- Y-Slope

Conclusion

The team has anticipated the alignment challenges AMSD presents by selecting the proper instrumentation:

> **IPI (& PhaseCam)**

> **Hexapod**

> **Diffractive Null**

> **Leica ADM**

A plan & algorithm are now in place to achieve measurement uncertainty less than half the surface requirement.

Several approaches are being pursued to further improve the measurement.